Entomologia Experimentalis et Applicata
FOUNDED 1958

DOI: 10.1111/eea.12994

Hydrogel baits pose minimal risk to non-target insects and beneficial species

Grzegorz Buczkowski
Department of Entomology, Purdue University, West Lafayette IN, 47907, USA

Accepted: 2 August 2020

Key words: invasive ants, pollinators, water-storing crystals, chemical control, toxic bait, hydrogel, bait formulation, non-target effect, foraging ants, Hymenoptera, pest control, conservation concern

Abstract

Invasive ants are a significant pest around the world and have negative impact on natural and agricultural environments. Chemical control is mainly accomplished with residual sprays and toxic baits. Hydrogel baits are a novel bait formulation that has proven highly effective against multiple invasive ant species, but potential non-target effects have not been investigated. The baits are typically saturated in 25% sucrose solution which makes them attractive to foraging ants and potentially non-target organisms such as pollinators. The objective of the current study was to perform field studies to assess the potential attractiveness of hydrogel baits to various pollinating and non-pollinating arthropods in a variety of ecosystems, including tallgrass prairies, urban pollinator gardens, and commercial apiaries. The study focused on social Hymenoptera as pesticides are acutely toxic to various Hymenoptera and have been implicated as one of the contributing factors in pollinator declines. Results show that Diptera were overwhelmingly the most common visitors and accounted for >40% of all visitors. Other common groups included beetles and yellowjackets. Common pollinating insects such as honeybees, solitary bees, and butterflies rarely visited the baits and accounted for ca. 3% of all visits and were never found on ground baits. Results show that the risk to pollinators is relatively low; most arthropods attracted to the baits were taxa that are extremely abundant, not of conservation concern, and in some cases pestiferous or invasive. The deployment of hydrogels for invasive ant control in areas where multiple invasive insect taxa are present may have the additional benefit of controlling multiple pests.

Introduction

Ants are common, dominant taxa in terrestrial environments and play key roles in ecosystem structure and function (Folgarait, 1998). However, many native and invasive ant species are also important pests in urban, agricultural, and natural ecosystems (Holway et al., 2002; Silverman & Brightwell, 2008). Chemical control of pestiferous ants is mainly accomplished with the use of toxic baits and residual sprays. Baits and sprays provide many important advantages and benefits including rapid implementation and ease of use, high effectiveness against pests with no resistance (e.g., ants), cost effectiveness, and ability to control large populations of pests over large areas. Although baits and sprays can be highly effective, they also have severe limitations. The main disadvantages of sprays are excessive non-target effects and little long-term impact (Desneux et al., 2007; Potts et al., 2010) which preclude broadcast applications in natural areas. Toxic baits are an alternative to sprays because they exploit the recruitment and food-sharing behavior of ants to maximize efficacy. Relative to sprays, baits reduce non-target and environmental effects because they require smaller amounts of insecticide and are more target-specific. However, granular baits are often not attractive to species that prefer liquid baits, and liquid baits have additional disadvantages including lack of effective dispensers, high cost to deploy and maintain stations, and spoilage under field conditions (Daane et al., 2008; Klotz et al., 2009).

To overcome problems associated with traditional pesticide treatments, a novel bait delivery method which relies on water-storing crystals (hydrogels) has been developed (Boser et al., 2014; Buczkowski et al., 2014a; Rust et al., 2015). Hydrogels are superabsorbent polymers (polyacrylamide) that readily absorb water and water-soluble materials, including toxicants (e.g., thiamethoxam) and

*Correspondence: E-mail: gbuczkow@purdue.edu

phagostimulants (e.g., sucrose). Hydrated crystals are then dispersed over the treatment area and allow ants to feed on a thin layer of liquid present on the surface. In addition to polyacrylamide hydrogels, a more biodegradable alternative consisting of alginate hydrogels has been developed (Tay et al., 2017; McCalla et al., 2020). Since initial development, hydrogels have proven highly effective against Argentine ants, *Linepithema humile* (Mayr), in various laboratory and field studies (Boser et al., 2014; Buczkowski et al., 2014a,b; Rust et al., 2015; McCalla et al., 2020). Laboratory studies have examined various aspects of hydrogel performance, stability, and efficacy. Hydrogels saturated in 25% sucrose solution containing 0.0007% thiamethoxam were highly effective against all castes and life stages of Argentine ants and required ca. 2 days to kill all workers and ca. 6 days to achieve complete mortality in queens and brood (Buczkowski et al., 2014a). Bait aging tests showed that the duration of outdoor exposure has a significant effect on moisture loss and subsequently bait acceptance and bait efficacy (Boser et al., 2014; Buczkowski et al., 2014a). In field studies, hydrogels saturated in 25% sucrose solution containing 0.0007% thiamethoxam have been shown to be highly effective against Argentine ants in agricultural (Buczkowski et al., 2014b), natural (Boser et al., 2014; Rust et al., 2015), and urban (Tay et al., 2017) settings.

Hydrogel baits offer numerous advantages because they provide ants with a liquid food source that is in a solid form, are easy to apply via ground and aerial applications, do not require stations that need to be serviced and refilled, are relatively inexpensive, and minimize insecticide use because they require relatively low amounts of active ingredient. However, hydrogels also have the potential to harm non-target organisms such as beneficial natural predators and pollinators, which might translate into ecosystem effects. Hydrogels are typically saturated in 25% sucrose solution which makes them attractive to foraging ants, and potentially to various vertebrates (e.g., birds, rodents) and non-vertebrates (e.g., insects). Such non-target effects are a significant concern in area-wide treatments in natural areas where native fauna conservation is a concern. In some cases, eradication attempts have been deemed inappropriate due to the delicate nature of the infested habitats and the presence of sensitive non-target wildlife (Abedrabbo, 1994; Marr, 2003). In other cases, ant eradication efforts have been stopped due to environmental concerns (van Schagen et al., 1994; Buhs, 2004).

The objective of the current study was to assess the potential effects of hydrogel baits on various pollinating and non-pollinating arthropods in field studies in tallgrass prairie, urban pollinator garden, and commercial apiary ecosystems. The study focused on social Hymenoptera as pesticides are acutely toxic to various Hymenoptera and have been implicated as one of the contributing factors in pollinator declines (Potts et al., 2010; Goulson et al., 2015; Long & Krupke, 2016). Hydrogel baits are typically formulated with ultralow doses of neonicotinoid pesticides such as thiamenthoxam (Boser et al., 2014; Buczkowski et al., 2014a,b; Rust et al., 2015); neonicotinoid pesticides (including thiamethoxam and its metabolite, clothianidin) have been shown to be toxic to pollinators (Alburaki et al., 2015; Rundlof et al., 2015; Calvo-Agudo et al., 2019).

Materials and methods

Non-ant arthropod attraction in urban pollinator gardens

The attraction of various pollinating and non-pollinating arthropods to hydrogels was evaluated in field experiments in five urban pollinator gardens located in Tippecanoe County, Indiana, USA: Horticulture Park Pollinator Garden (40°25′28.4″N, 86°56′02.9″W), Entomology Field Operations Building Pollinator Garden (40°25′42.8″N, 86°56′56.1″W), Columbian Park Pollinator Garden (40°24′48.1″N, 86°52′11.8″W), Pao Hall Pollinator Garden (40°25′21.2″N, 86°54′56.8″W), and Whistler Hall Pollinator Garden (40°25′20.0″N, 86°54′46.8″W). The gardens were planted with a wide range of perennial and annual plants that provided season-round sources of nectar and pollen. To prepare the crystals, 20 g of water-storing crystals (100% polyacrylamide; Miracle Gro Lawn Products, The Scotts Company, Marysville, OH, USA) was added to 1 l of 25% sucrose solution in water and allowed 1 h to saturate. Because the study focused on attractiveness and not efficacy, blank hydrogels were tested and no insecticide was included. At each location, 12 hydrogel placements were made along a 7.5-m transect: six ground placements separated by 1.5 m and six platform placements located 1 m above ground placements. For ground placements, 5 g of sucrose-infused hydrogels was placed in a plastic weigh dish (7.5 cm diameter, 2 cm deep) and the dish was placed at the base of plants attracting pollinators. For platform placements, a 1-m garden stake was inserted into the ground and a 15 × 15 cm plywood panel was attached horizontally to the top of the stake. A weigh dish containing 5 g of sucrose-infused hydrogels was placed on top of the platform, roughly at the height of flowering plants. The number of all non-ant visitors present within the dishes was recorded for 4 h (from 09:00 to 13:00 h).

An observer continuously scanned all gel placements throughout the 4-h period and tabulated the total number of visitors in 1-h intervals. A period of 4 h was selected because previous tests demonstrated that hydrogels aged for >4 h were significantly less attractive relative to fresh hydrogels or those aged for 1, 2, or 4 h (Buczkowski et al., 2014a). Arthropods visiting the bait dishes were visually identified as: spiders (Araneae), springtails (Collembola), woodlice (Isopoda), butterflies/moths (Lepidoptera), beetles (Coleoptera), hover flies (Diptera, Syrphidae), fruit flies (Diptera, Drosophilidae), flesh flies (Diptera, Sarcophagidae), house flies (Diptera, Muscidae), other flies (miscellaneous Diptera), thin waist wasps (Hymenoptera, Sphecidae), yellowjackets (Hymenoptera, Vespidae), honeybees/bumblebees (Hymenoptera, Apidae), solitary bees (misc. Hymenoptera), and parasitoids (misc. Hymenoptera). The study focused specifically on non-target (non-ant) visitors and the presence of ants was not recorded. Preliminary observations revealed that ants were occasionally present on ground placements, but never on platform placements. Furthermore, behavioral interference (aggression) between ants and non-ants was never observed. The number of non-ant visitors was tallied for all experimental replicates. The experiment was replicated across two consecutive years, 2017 and 2018, at all test sites. Additionally, within each year, the experiment was conducted at two distinct seasons, late spring (May) and early fall (September), to capture the greatest diversity of arthropods that might be foraging for nectar and pollen.

Non-ant arthropod attraction in restored prairie ecosystems

In addition to evaluating hydrogels in urban pollinator gardens, the attraction of pollinators was evaluated in restored tallgrass prairies. Tallgrass prairies are characterized by high plant and forb diversity and typically support high pollinator diversity (Hines & Hendrix, 2005; Roulston & Goodell, 2011; Harmon-Threatt & Chin, 2016). The attraction of pollinators and other arthropods to hydrogels was assessed in three prairies in Tippecanoe County, IN, USA: Scifres-Maier Nature Preserve (40°27′14.6″N, 86°56′22.6″W), Prophetstown State Park (40°30′48.7″N, 86°48′40.7″W), and Clegg Botanic Gardens (40°26′40.3″N, 86°49′42.6″W). As above, 10 hydrogel placements were made at each location (five ground and five platform). All non-ant visitors present within the dishes were recorded continuously for 4 h (from 09:00 to 13:00 h) and tallied hourly for each experimental replicate as above. The survey was performed in September 2019 during the fall bloom which included mainly New England asters [*Symphyotrichum novae-angliae* (L.) GL Nesom], stiff goldenrods (*Solidago rigida* L.), white heath asters [*Symphyotrichum ericoides* (L.) GL Nesom], false sunflowers [*Heliopsis helianthoides* (L.) Sweet], and prairie milkweeds (*Asclepias sullivantii* Engelm. ex A.Gray).

Honeybee attraction in a commercial apiary

The attraction of honeybees, *Apis mellifera* L. (Hymenoptera: Apidae), to hydrogel baits was evaluated in an apiary maintained by the Department of Entomology at Purdue University (40°25′42.8″N, 86°56′56.1″W). The apiary consists of two separate sites (Bee Lab 1 with 25 hives and Bee Lab 2 with 30 hives) separated by approximately 150 m. At each location, six wooden platforms (40 × 40 × 20 cm high) were placed in a grassy field surrounding the hives. The platforms were placed along a 50-m transect (10 m apart), approximately 10 m from hive entrances, and in direct pathway of foraging bees. Five g of hydrogel bait, dispensed form plastic weigh dish, was placed on top of each platform. The number of honeybees present within the dishes was recorded every hour for 4 h at each site (from 09:00 to 13:00 hours). The survey was performed in May 2016 during the spring bloom which included mainly bush honeysuckle (*Lonicera tatarica* L.), black locust (*Robinia pseudoacacia* L.), and autumn olive (*Elaeagnus umbellata* Thunb.).

Statistical analysis

All data analyses were performed using STATISTICA v.13.2 software (StatSoft, Tulsa, OK, USA). Wilcoxon signed-rank test was conducted separately for each of the three test sites on cumulative arthropod counts across test factors, including ground vs. platform placement and season.

Results

Non-ant arthropod attraction in urban pollinator gardens

In total 515 non-ant arthropods were observed on the 240 hydrogel baits placed in the field for a total of 80 h (960 bait h) (Figure 1; Table 1). This is equivalent to 2.15 arthropods per hydrogel placement or 0.54 observed visits per h per bait. Diptera – consisting collectively of hover flies, fruit flies, flesh flies, house flies, and other flies – were overwhelmingly the most common visitors and accounted for 48% (247/515) of all visitors. Diptera observed on ground placements were 51% (117/229), not significantly different from the 45% (130/286) observed on platform placements (Wilcoxon signed-rank test: $Z = 0.70$, $P = 0.54$). Other common groups included beetles (16.5%) and yellowjackets (15.5%). All other groups accounted for <5% each of total counts (Table 1). Common pollinating insects such as honeybees comprised 4.2% of the total, solitary bees 1.6%, and butterflies 0.6%. Interestingly, no honeybees, solitary bees, or butterflies were ever observed on ground placement, all visits were to platform placements. Platform placements typically attracted more visitors relative to ground placements (Figure 1), but the 286 visitors recorded on platforms was not significantly different from the 229 visitors recorded on the ground ($Z = 1.38$, $P = 0.17$). Most visits to ground and platform placements occurred during the first 2 h (Figure 1A) and the total number of visitors on ground and platform placements in the first 2 h was significantly higher than in the last 2 h (Z = 6.78, P<0.0001). Regarding seasonal comparisons, the number of visitors recorded in May (combined for 2017 and 2018) was 262, not significantly different from the 253 visitors recorded in September (Z = 0.23, P = 0.81).

Non-ant arthropod attraction in restored prairie ecosystems

In restored prairies, in total 109 arthropods were observed on 30 hydrogel placements over a total of 12 h (120 bait h). This is equivalent to 3.63 arthropods per bait placement or 0.91 visits per h. As in urban pollinator gardens, various species of Diptera were overwhelmingly the most common visitors and accounted for 39% (42/109) of all visitors (Table 2). Within Diptera, 48% were observed on ground placements and 52% on platform placements (Wilcoxon signed-rank test: Z = 0.36, P = 0.84). Similar to pollinator gardens, the two next most common taxa were beetles (19.3%) and yellowjackets (12.8%). All other groups accounted for <5% each of total counts (Table 2). The total number of visitors recorded on platform placements was 44 and not significantly different from the 65 visitors recorded on ground placements (Z = 0.53, P = 0.59). Hymenopteran pollinators (honeybees and bumblebees) accounted for only 3.6% of all visitors and Lepidopteran pollinators (butterflies and moths) accounted for 3.6% of all visitors, but none occurred on ground placements. Most visits to ground and platform placements occurred during the first 2 h (Figure 1C) and the total number of visitors on ground and platform placements in the first 2 h was significantly higher than in the last 2 h (Z = 2.80, P = 0.005).

Honeybee attraction in a commercial apiary

In total 15 honeybees were observed on 12 platform hydrogel baits over a total of 8 h (48 bait h). This is equivalent to 1.25 bees per placement or 0.31 visits per h per bait. The majority of bait placements, seven out of 12 (58%), did not have any bee visits during the 4-h testing period. For the remaining five baits, most visits occurred during the 1st h (53%), and declined to 27% during the 2nd h, 20% during the 3rd, and no bees visited the baits during the 4th h.

Discussion

Non-target impacts are often a significant concern in large-scale ant eradication programs (Boser et al., 2016; Hoffmann et al., 2016; Buczkowski, 2017) and successful control efforts must be carefully planned, delivered, and evaluated (Hoffmann et al., 2010, 2011). The results of the current study demonstrate that hydrogel baits, although potentially attractive to certain groups of non-target arthropods, are generally safe for hymenopteran and lepidopteran pollinators such as bees and butterflies. The results obtained for gardens and prairie sites demonstrated that Diptera, consisting of various species of flies, were the most common visitors and accounted for approximately half of all visitors. Within Diptera, fruit flies were the most common and accounted for >50% of all visitors in garden and prairie ecosystems. Diptera are often neglected, but an important group of pollinators in natural and agricultural

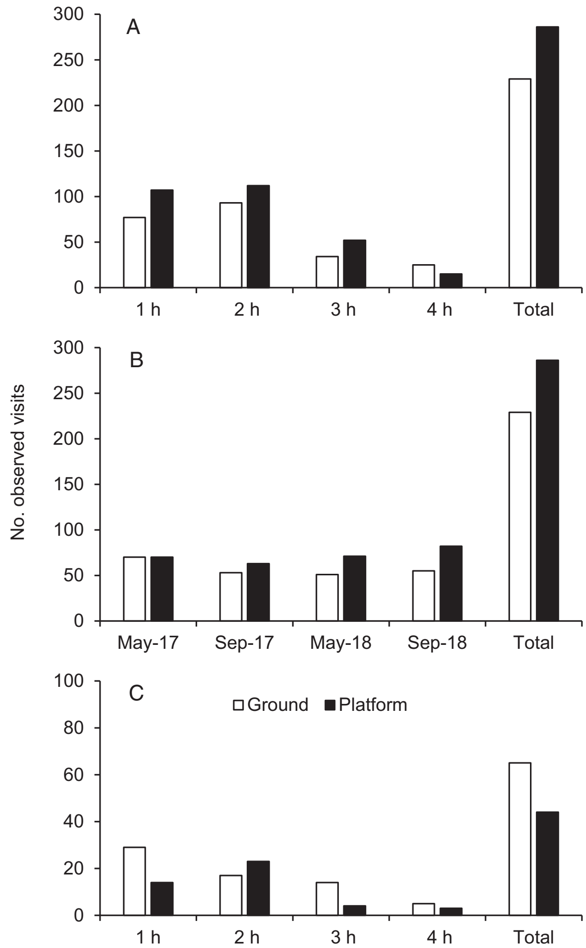

Figure 1 Arthropod diversity on ground and platform placements of hydrogel crystals in urban pollinator gardens and natural prairies. (A) Hourly and total number of non-ant visits in pollinator gardens. (B) Total and seasonal number of non-ant visits in pollinator gardens in spring and fall of 2017 and 2018. (C) Hourly and total number of non-ant visits in natural prairies. Totals are summed across all test sites and survey periods. Note the difference in scale on the vertical axes.

Table 1 Arthropod diversity on ground and platform placements of hydrogel baits in urban pollinator gardens. Numbers are total for five pollinator gardens. Top row is counts on ground placements and bottom row is counts on platform placements

Taxon (non-ant visitors)	Order	Family	May 2017	Sept 2017	May 2018	Sept 2018	Total, no. (%)
Spiders	Araneae		3	1	1	1	6 (2.6)
			3	0	3	0	6 (2.1)
Springtails	Collembola		11	4	9	2	26 (11.4)
			0	0	0	0	0 (0)
Woodlice	Isopoda		1	4	2	0	7 (3.1)
			0	0	0	0	0 (0)
Butterflies/moths	Lepidoptera		0	0	0	0	0 (0)
			0	1	1	1	3 (1.1)
Beetles	Coleoptera		16	4	12	12	44 (19.2)
			11	2	17	11	41 (14.4)
Hover flies	Diptera	Syrphidae	0	4	1	0	5 (2.2)
			5	3	1	2	11 (3.9)
Fruit flies	Diptera	Drosophilidae	17	15	17	14	63 (27.5)
			16	15	25	14	70 (24.6)
Flesh fly	Diptera	Sarcophagidae	10	5	0	1	16 (7.0)
			5	3	2	4	14 (4.9)
House fly	Diptera	Muscidae	3	0	6	7	16 (7.0)
			8	3	5	6	22 (7.7)
Other fly	Diptera	Unknown	9	3	3	2	17 (7.4)
			5	0	6	2	13 (4.6)
Thin waist wasp	Hymenoptera	Sphecidae	0	0	0	0	0 (0)
			7	4	5	4	20 (7.0)
Yellowjackets	Hymenoptera	Vespidae	0	13	0	16	29 (12.7)
			0	23	0	28	51 (17.9)
Honeybees, bumblebees	Hymenoptera	Apidae	0	0	0	0	0 (0)
			9	8	9	13	22 (7.7)
Solitary bees	Hymenoptera	Various	0	0	0	0	0 (0)
			4	1	2	2	8 (2.8)
Parasitoid	Hymenoptera	Various	0	0	0	0	0 (0)
			1	0	3	0	4 (1.4)
Total			70	53	51	55	229 (100)
			70	63	71	82	286 (100)

ecosystems (Orford et al., 2015; Raguso, 2020). Many dipteran families include flies that feed at flowers as adults and more than 550 species of wild and cultivated plants are regularly visited by Diptera (Larson et al., 2001). Coleoptera (beetles) were the second most common visitors and accounted for an average of 17.9% of all visitors, followed by Hymenoptera (wasps, mainly yellowjackets) which accounted for an average of 14.2% of all visitors. Common pollinating insects, such as bees and butterflies, accounted for approximately 4 and 2% of all visitors, respectively (averaged across gardens and prairies). Results obtained for urban gardens and tallgrass prairies were highly consistent with Diptera being the most common, followed by Coleoptera, and Hymenoptera. This is surprising given that urban pollinator gardens and tallgrass prairies differ vastly with regard to patch size, type of vegetation, proximity to urban areas, environmental factors, and a variety of other factors. On the other hand, the results may simply reflect community-wide richness across ecosystems. In the USA, Diptera (19 600 spp.), Coleoptera (23 700 spp.), and Hymenoptera (17 500 spp.) are the three most diverse and most abundant insect groups and extremely common in most ecosystems (Borror et al., 1989).

Results show that hydrogel baits are, to some extent, attractive to non-target organisms including pollinators. However, the risk to pollinators is relatively low as most arthropods attracted to the baits were taxa that are extremely abundant, not of conservation concern, and in some cases, pestiferous or invasive. In both gardens and prairies, fruit flies, beetles, and yellowjackets collectively accounted for 70–80% of all visitors. Fruit flies were the most

Table 2 Arthropod diversity on ground and platform placements of hydrogel baits in tallgrass prairies. Numbers are total for three prairies. Top row is counts on ground placements and bottom row is counts on platform placements

Taxon (non-ant visitors)	Order	Family	Sept 2019 total no. (%)
Spiders	Araneae		4 (6.2)
			0 (0)
Springtails	Collembola		15 (23.1)
			0 (0)
Woodlice	Isopoda		2 (3.1)
			0 (0)
Butterflies/moths	Lepidoptera		0 (0)
			4 (9.1)
Beetles	Coleoptera		16 (24.6)
			5 (11.4)
Hover flies	Diptera	Syrphidae	0 (0)
			4 (9.1)
Fruit flies	Diptera	Drosophilidae	13 (20.0)
			13 (29.5)
Flesh fly	Diptera	Sarcophagidae	0 (0)
			2 (4.5)
House fly	Diptera	Muscidae	5 (7.7)
			1 (2.3)
Other fly	Diptera	Unknown	2 (3.1)
			2 (4.5)
Thin waist wasp	Hymenoptera	Sphecidae	0 (0)
			3 (6.8)
Yellowjackets	Hymenoptera	Vespidae	8 (12.3)
			6 (13.6)
Honeybees,	Hymenoptera	Apidae	0 (0)
bumblebees			4 (9.1)
Solitary bees	Hymenoptera	Various	0 (0)
			0 (0)
Parasitoid	Hymenoptera	Various	0 (0)
			0 (0)
Total			65 (100)
			44 (100)

common visitors and accounted for roughly a quarter of all visits. Although fruit flies fill important ecological niches in natural ecosystems, they are nuisance pests in urban environments, confined animal production, and among the most destructive pests in agriculture (Aluja & Mangan, 2008). Many invasive fruit fly species, including the oriental fruit fly, the Mediterranean fruit fly, and spotted-wing drosophila are extremely destructive pests in fruit and vegetable production. The Mediterranean fruit fly (medfly) is considered the most important agricultural pest in the world (Szyniszewska & Tatem, 2014). Similarly, yellowjackets were frequently attracted to hydrogel baits and comprised approximately 15% of visitors.

Yellowjackets, which are carnivores, play an important role in the ecosystem mainly because they prey on pest insects in natural and agricultural environments. On the other hand, many yellowjacket species are pests in urban environments and some invasive species have significantly impacted the ecological integrity of natural ecosystems (Beggs, 2001; Hanna et al., 2012). Several invasive yellowjacket species threaten biodiversity and have been shown to reduce the densities of endemic taxa in invaded ecosystems (Wilson et al., 2009). Hydrogel baits are typically used to control invasive ants, but in certain situations could have the added benefit of controlling multiple pest or invasive species in a single application. Additional steps to further minimize the potential negative effects of hydrogels on non-targets could include changes in application methods. First, timing of application might be important as most pollinators are day active and forage only during specific times of the day, typically midday (Bloch et al., 2017). Therefore, hydrogel application in late afternoon or evening might reduce or eliminate the potential of pollinators coming into contact with hydrogels. Second, clumped rather than dispersed applications might further reduce the potential of non-target contact with the hydrogels as many non-targets are solitary foragers and reducing hydrogel density might lead to smaller chance of exposure.

In all test sites, including pollinator gardens, tallgrass prairies, and apiaries, most visits to hydrogel placements occurred during the first 2 h. Previous studies show that depending on environmental conditions hydrogel baits experience water loss of about 50% in the 1st 6–9 h are the most attractive when fully hydrated (Buczkowski et al., 2014a; Rust et al., 2015). Studies also show that water loss has a negative effect on hydrogel acceptance and concurrently hydrogel efficacy (Buczkowski et al., 2014a; Rust et al., 2015). In studies with Argentine ants, hydrogels aged for 1 or 2 h were significantly less attractive relative to fresh hydrogels, but there was no difference in mortality caused by fresh hydrogels vs. those aged for 1–2 h (Buczkowski et al., 2014a). Furthermore, field studies show that hydrogel baits are highly effective in controlling Argentine ants (Boser et al., 2014; Buczkowski et al., 2014b; Rust et al., 2015). This suggests that the 2-h feeding window is sufficient for achieving satisfactory control. The relatively fast water loss experienced by hydrogel baits may be important for protecting pollinators and other non-target organisms. Partially or fully dehydrated hydrogels should be less attractive to non-targets. Additionally, any unconsumed toxicant presumably remains in the matrix, further minimizing non-target exposure. In a field study in California, USA, to eradicate invasive Argentine ants from Santa Cruz Island, >94% of visits to hydrogel baits were by Argentine ants and the remaining 6% mainly by isopods and other abundant and non-sensitive arthropods (Boser et al., 2014).

In conclusion, hydrogel baits have only a slight potential to harm non-target organisms, including hymenopteran pollinators. However, the risk to pollinators is relatively low as only 3.8% of all visitors were bees, 0.02 bees visited a bait placement per h, and 79% of bait placements were never visited by bees. Additionally, any harmful effects would likely be compensated because reducing or eliminating invasive ant populations with hydrogel applications should help increase the survival of ground-dwelling arthropods, pollinators, and various plant species that the pollinators feed on. Studies show that invasive ants have a strong negative effect on native species and disrupt key ecological functions such as nutrient cycling, seed dispersal, and pollination services (Holway et al., 2002; Lach, 2007; LeVan et al., 2014; Hanna et al., 2015). Invasive ants are attracted to flowers for their nectar and are detrimental to the reproduction of many plant species because they are poor pollinators and generally regarded as 'nectar thieves' (Lach, 2007; Bleil et al., 2011). Furthermore, ants harm plants by associating with honeydew-producing hemipterans (Holway et al., 2002; Lach, 2007) and preying on pollinating insects and other floral arthropods (Lach, 2007; Sinu et al., 2017). Therefore, the benefits of hydrogels should outweigh any potential drawbacks and have an overall positive effect on ecosystem health.

Acknowledgements

I thank K. Given for assistance with field trials at the apiary and D. Richmond for advice on data analysis. Financial support was provided in part by the Center for Urban and Industrial Pest Management and the Industrial Affiliates Program at Purdue University.

References

Aluja M & Mangan RL (2008) Fruit fly (Diptera: Tephritidae) host status determination: critical conceptual, methodological, and regulatory considerations. Annual Review of Entomology 53: 473–502.

Abedrabbo S (1994) Control of the little fire ant, *Wasmannia auropunctata*, on Santa Fe Island in the Galapagos Islands. Exotic Ants: Biology, Impact, and Control of Introduced Species (ed. by DF Williams), pp. 219–227. Westview Press, Boulder, CO, USA.

Alburaki M, Boutin S, Mercier P-L, Loublier Y, Chagnon N & Derome N (2015) Neonicotinoid-coated *Zea mays* seeds indirectly affect honeybee performance and pathogen susceptibility in field trials. PLoS ONE 10: e0125790.

Beggs J (2001) The ecological consequences of social wasps (*Vespula* spp.) invading an ecosystem that has an abundant carbohydrate resource. Biological Conservation 99: 17–28.

Bleil R, Bluthgen N & Junker RR (2011) Ant-plant mutualism in Hawaii? Invasive ants reduce flower parasitism but also exploit floral nectar of the endemic shrub *Vaccinium reticulatum* (Ericaceae). Pacific Science 65: 291–300.

Bloch G, Bar-Shain N, Cytter Y & Green R (2017) Time is honey: circadian clocks of bees and flowers and how their interactions may influence ecological communities. Philosophical Transactions of the Royal Society B 372: 20160256.

Borror, DJ, Triplehorn, CA & Johnson, NF (1989) An Introduction to the Study of Insects. Philadelphia, PA, US: Saunders College Publishing

Boser CL, Hanna C, Faulkner KR, Cory C, Randall J & Morrison SA (2014) Argentine ant management in conservation areas: results of a pilot study. Monographs of the Western North American Naturalist 7: 518–530.

Boser CL, Hanna C, Holway DA, Faulkner KR, Naughton I et al. (2016) Protocols for Argentine ant eradication in conservation areas. Journal of Applied Entomology 141: 540–550.

Buczkowski G, Roper E & Chin D (2014a) Polyacrylamide hydrogels: an effective tool for delivering liquid baits to pest ants. Journal of Economic Entomology 107: 748–757.

Buczkowski G, Roper E, Chin D, Mothapo N & Wossler T (2014b) Hydrogel baits with low-dose thiamethoxam for sustainable Argentine ant management in commercial orchards. Entomologia Experimentalis et Applicata 153: 183–190.

Buczkowski G (2017) Prey-baiting as a conservation tool: selective control of invasive ants with minimal non-target effects. Insect Conservation and Diversity 10: 302–309.

Buhs JB (2004) The Fire Ant Wars. University of Chicago Press, Chicago, IL, USA.

Calvo-Agudo M, Gonzalez-Cabrera J, Pico Y, Calatayud-Vernich P, Urbaneja A et al. (2019) Neonicotinoids in excretion product of phloem-feeding insects kill beneficial insects. Proceedings of the National Academy of Sciences of the USA 116: 16817–16822.

Daane KM, Cooper ML, Sime KR, Nelson EH, Battany MC & Rust MK (2008) Testing baits to control Argentine ants (Hymenoptera: Formicidae) in vineyards. Journal of Economic Entomology 101: 699–709.

Desneux N, Decourtye A & Delpuech JM (2007) The sublethal effects of pesticides on beneficial arthropods. Annual Review of Entomology 52: 81–106.

Folgarait PJ (1998) Ant biodiversity and its relationship to ecosystem functioning: a review. Biodiversity and Conservation 7: 1221–1244.

Goulson D, Nicholls E, Botias C & Rotheray EI (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347: 1255957.

Hanna C, Foote D & Kremen C (2012) Short- and long-term control of *Vespula pennsylvanica* in Hawaii by fipronil baiting. Pest Management Science 68: 1026–1033.

Hanna C, Naughton I, Boser C, Alarcon R, Hung K-LJ & Holway DA (2015) Floral visitation by the Argentine ant reduces bee visitation and plant seed set. Ecology 96: 222–230.

Harmon-Threatt A & Chin K (2016) Common methods for tallgrass prairie restoration and their potential effects on bee diversity. Natural Areas Journal 36: 400–411.

Hines HM & Hendrix SD (2005) Bumble bee (Hymenoptera: Apidae) diversity and abundance in tallgrass prairie patches: effects of local and landscape floral resources. Environmental Entomology 34: 1477–1484.

Holway DA, Lach L, Suarez AV, Tsutsui ND & Case TJ (2002) The causes and consequences of ant invasions. Annual Review of Ecology and Systematics 33: 181–233.

Hoffmann BD, Abbott KL & David P (2010) Invasive ant management. Ant Ecology (ed. by L Lach, CL Parr & KL Abbott), pp. 287–304. Oxford University Press, Oxford, UK.

Hoffmann BD, Davis P, Gott K, Jennings C, Joe S et al. (2011) Improving ant eradications: details of more successes, a global synthesis and recommendations. Aliens 31: 16–23.

Hoffmann BD, Luque GM, Bellard C, Holmes ND & Donlan CJ (2016) Improving invasive ant eradication as a conservation tool: a review. Biological Conservation 198: 37–49.

Klotz JH, Rust MK, Field HC, Greenberg L & Kupfer K (2009) Low impact directed sprays and liquid baits to control Argentine ants (Hymenoptera: Formicidae). Sociobiology 54: 101–108.

Lach L (2007) A mutualism with a native membracid facilitates pollinator displacement by Argentine ants. Ecology 88: 1994–2004.

Larson BMH, Kevan PG & Inouye DW (2001) Flies and flowers: the taxonomic diversity of anthophiles and pollinators. Canadian Entomologist 133: 439–465.

LeVan KE, Hung K-LJ, McCann KR, Ludka JT & Holway DA (2014) Floral visitation by the Argentine ant reduces pollinator visitation and seed set in the coast barrel cactus, *Ferocactus viridescens*. Oecologia 174: 163–171.

Long EY & Krupke CH (2016) Non-cultivated plants present a season-long route of pesticide exposure for honeybees. Nature Communications 7: 11629.

Marr R (2003) Toxic Baiting of the Yellow Crazy Ant, *Anoplolepis gracilipes*, on Christmas Island: Impacts on Non-Target Litter Vertebrates. Honours thesis, School of Biological Science, Monash University, Melbourne, Australia.

McCalla, KA, Tay, J-W, Mulchandani, A, Choe, D-H & Hoddle, MS (2020) Biodegradable alginate hydrogel bait delivery system effectively controls high-density populations of Argentine ant in commercial citrus. Journal of Pest Science, 931031–1042.

Orford KA, Vaughan IP & Memmott J (2015) The forgotten flies: the importance of non-syrphid Diptera as pollinators. Proceedings of the Royal Society B 282: 20142934.

Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O & Kunin WE (2010) Global pollinator declines: trends, impacts and drivers. Trends in Ecology & Evolution 25: 345–353.

Raguso RA (2020) Don't forget the flies: dipteran diversity and its consequences for floral ecology and evolution. Applied Entomology and Zoology 55: 1–7.

Roulston TH & Goodell K (2011) The role of resources and risks in regulating wild bee populations. Annual Review of Entomology 56: 293–312.

Rundlof M, Andersson GK, Bommarco R, Fries I, Hederstrom V et al. (2015) Seed coating with neonicotinoid insecticide negatively affects wild bees. Nature 521: 77–80.

Rust MK, Soeprono A, Wright S, Greenberg L, Choe D-H et al. (2015) Laboratory and field evaluations of polyacrylamide hydrogel baits against Argentine ants (Hymenoptera: Formicidae). Journal of Economic Entomology 108: 1228–1236.

van Schagen JJ, Davis PR & Widmer MA (1994) Ant pests of Western Australia, with particular reference to the Argentine ant (*Linepithema humile*). Exotic Ants: Biology, Impact, and Control of Introduced Species (ed. by DF Williams), pp. 174–180. Westview Press, Boulder, CO, USA.

Silverman J & Brightwell RJ (2008) The Argentine ant: challenges in managing an invasive unicolonial pest. Annual Review of Entomology 53: 231–252.

Sinu PA, Sibisha VC, Reshmi MVN, Reshmi TVJ, Aswathi K & Megha PP (2017) Invasive ant (*Anoplolepis gracilipes*) disrupts pollination in pumpkin. Biological Invasions 19: 2599–2607.

Szyniszewska AM & Tatem AJ (2014) Global assessment of seasonal potential distribution of Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae). PLoS ONE 9(11): e111582.

Tay J-W, Hoddle MS, Mulchandani A & Choe D-H (2017) Development of an alginate hydrogel to deliver aqueous bait for pest ant management. Pest Management Science 73: 2028–2038.

Wilson EE, Mullen LM & Holway DA (2009) Life history plasticity magnifies the ecological effects of a social wasp invasion. Proceedings of the National Academy of Sciences of the USA 106: 12809–12813.